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Risk-based Technology Methodology for the Safety Assessment of Marine Compressed Natural Gas Fuel Systems

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ABSTRACT

The introduction of alternative fuels (other than diesel oil or gasoline) for some commercially operated marine vessels presents a problem to marine regulators and designers since accepted standards and U.S. Coast Guard policy have not been established. Establishing safe design criteria is a common problem with the introduction of new technologies, novel concepts, and complex systems. In order to determine design safety for novel marine concepts such as compressed natural gas (CNG) fuel, a formal system safety approach may be used. Risk-based technologies (RBT) provide techniques to facilitate the proactive evaluation of system safety through risk assessment, risk control, risk management, and risk communication. The proposed outfitting of a CNG fuel system on the KINGS POINTER training vessel is discussed as a specific marine application of CNG fuel and an appropriate situation for applying system safety techniques.

INTRODUCTION

Alternative Fuels

Alternative fuels such as methane (natural gas), propane, and hydrogen are being introduced as new fuel sources for a variety of uses including automobiles, mass transportation, and marine vehicles. These fuels may be used for operating both conventional engine designs such as diesels and novel designs such as fuel cells. Recent legislation has catalyzed the introduction of alternative fuels for use in the United States transportation system. The Clean Air Act Amendments of 1990 mandates the reduction of exhaust emissions from mobile sources. The National Energy Policy Act of 1992 sets a goal for 30% use of alternative fuels by the year 2010. States have also created statutes addressing the use of alternative fuels [1]. These laws are promoting the use of alternative fuels because technology may not be able to economically implement the clean air laws for conventional diesel/gasoline powered systems. In addition to reductions in air pollution some alternative fuels are more cost effective than conventional fuels. For example, fuel capital costs for combined CNG and diesel fuel engines have been shown to decrease by up to 30% compared to diesel engines [2]. Although initial costs for alternative fuel systems may be greater than conventional fueled engines, the operational life-cycle costs have been shown to be competitive with conventional fuels in some applications.

Numbers in brackets refer to references at the end of the paper.

The trend to lower pollution through decreased emission requirements will result in the need for cleaner burning fuels and/or technologies for marine applications. In addition, the depletion of the world's oil reserves is promoting the use of alternative fuels like CNG. Mass transit providers are receiving federal, state and local incentives to use alternative fuels to reduce the dependency on oil and reduce pollution [3].

In the marine industry, the movement to switch to alternative fuels has not matched the same momentum as the automotive industry which currently has over 800,000 CNG vehicles in operation worldwide [4]. This can largely be attributed to the lack of emission standards in the United States for marine engines. However, this situation may change as new international and domestic regulations are under development. The International Maritime Organization has established guidelines for engine emissions in Annex VI of MARPOL 73/77 "Regulations for the Prevention of Air Pollution from Ships." The United States has not yet ratified Annex VI, but may do so in the future. The Environmental Protection Agency has also proposed a program for controlling marine emissions from U.S. flagged ships. A notice of proposed rulemaking was published on December 11, 1998 addressing proposed requirements for emission standards on marine engines above 37 kilowatts. Taken as a whole, the trend for more stringent air quality standards may influence the need for alternative fuels.

Issues with the marine application of CNG have been introduced through several projects. There has been one passenger ferry that received U.S. Coast Guard approval for CNG use in 1995 (JAMES C. ECHOLS). Also, research was conducted on converting a Gulf Coast shrimp boat to LNG fuel [5]. LNG fuel is converted to CNG fuel through boil-off, prior to use as fuel in the engine. Internationally, there have been several applications of CNG powered ferries. Currently, the KINGS POINTER training vessel (U.S. Merchant Marine Academy) is undergoing plan review at the Coast Guard's Marine Safety Center for conversion to CNG fuel. These initial applications for marine vessels are helping to identify the relevant safety issues for marine use of CNG.

Regulatory Challenge of New Technologies

The introduction of new technologies and designs, such as CNG fuel systems, pose a problem for the safety evaluation of marine systems. System designs beyond the scope of existing regulations raise safety concerns due to the introduction of uncertainty, new hazards, and/or system complexities. There is an absence of specific standards for the application of CNG fuel for machinery systems on vessels other than LNG cargo vessels. CNG is a relatively new fuel with little operating experience in the commercial ship industry as compared to conventional fuels. Conventional fuel systems using diesel oil and gasoline have been used for many years with a proven safety record as well as established regulations and design standards. There may also be a higher "public acceptance" with traditional fuels due to familiarity.

Traditional regulation of conventional marine design has relied upon a level of risk that is intuitively accepted over the years, based on accepted design standards and operational history. System "experts" are often used to establish safe criteria for system designs based on intuition and experience [6]. Conservative requirements may result in an over-design of the marine system, affecting other areas of performance such as capital cost. If the operation of a ship is considered unsafe due to some maritime disaster or system failure, the regulations may be changed as a reaction to improve the level of safety. This traditional reactive approach to safety may result in long periods of time for development, possible severe consequences to the public, and a high level of uncertainty about the safety performance of the design. A reactive approach to managing safety will always exist because of the constant demand for improving safety and the fact that risk cannot be completely eliminated. However, there are other methods of risk management that proactively provide adequate levels of safety for marine systems that lack an adequate performance history.

Novel marine designs require the regulator and the system designer to work together to determine if the new design and operating conditions meet an acceptable level of safety when compared to conventional craft designs. Due to the lack of prescribed regulations, an organized method for establishing safety performance needs to be established. Safety performance is defined as the ability of a system to control potential risks.

System Safety

The need to understand the safety performance of a novel design has prompted the application of established safety technologies. The use of alternative fuels, such as CNG, require the use of a systematic safety approach to thoroughly address the potential hazards of this fuel [1]. A system safety approach offers a comprehensible method to identify and mitigate the risks of a system through risk modeling. Once risks are identified and prioritized, appropriate action can be taken to mitigate the risk to acceptable levels. This technique is different from traditional design compliance determinations since a system safety approach evaluates an acceptable design from estimates of safety performance rather than prescribed regulations.

A system safety approach using RBT is composed of four major categories as identified in Figure 1: risk assessment, risk control, risk management, and risk communication. Risk assessment identifies safety hazards, consequences and estimates their probabilities of occurrence. Risk control provides engineering design or administrative/operational features to mitigate risk. Risk management uses risk assessment results, control alternatives, and additional factors to make decisions. Risk communication provides a common understanding of the relevance of certain risks among diverse groups of individuals. Additional descriptions of these technologies are detailed in this paper.

System safety should be an ongoing process addressing hazards throughout the life-cycle of a CNG fuel system. This approach should continuously assess the hazards that are relevant to system design, operation, and maintenance.

This paper presents a methodology for applying risk-based technologies for the safety evaluation of marine systems; with specific examples pertaining to CNG fuel for marine use. This general approach may be applied to the safety determinations of novel systems where established rules, regulations, and guidelines are not available. Special areas of consideration for CNG safety evaluation include: fuel properties, system design, operation, maintenance, and personnel training. This technique is currently being applied to the U.S. Coast Guard Marine Safety Center's review of the KINGS POINTER training vessel engine conversion to CNG fuel.

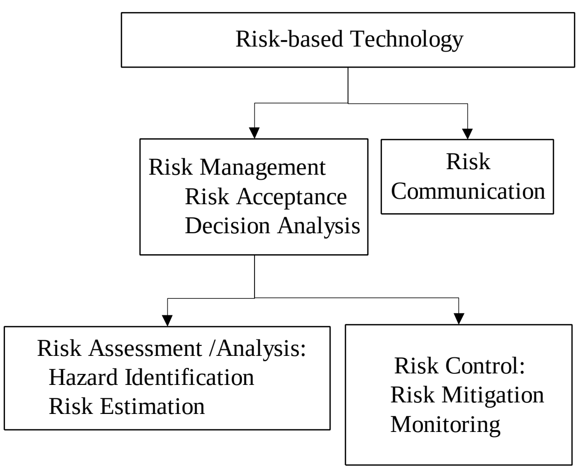

Fig. 1 Risk-based Technology [7]

NATURAL GAS FUEL

Applications in the Marine Industry

Liquefied Natural Gas (LNG) has been safely transported as cargo by ships since the METHANE PIONEER demonstrated the feasibility in 1959 [5]. Since this introduction, numerous voyages have been made with LNG as cargo. One product from LNG cargo is CNG resulting from the slow boiling of LNG fuel. Vent gas from the boil-off of LNG has been used as fuel for powering LNG carrier's main propulsion and auxiliaries. There are existing U.S. regulations and ABS classification society standards dealing with this specific application of CNG fuel for LNG cargo vessels, however, regulations are not available for application on other vessel types. This presents a problem in selecting appropriate design criteria for CNG systems of different vessel types.

Almost any gasoline or diesel-powered engine can run on compressed natural gas. The conversion of engines to run on CNG does not radically change the design or operating characteristics [8]. CNG may be readily used in spark ignition engines, but its high ignition temperature required the addition of diesel oil fuel for use in diesel engines. CNG engines may be "bi-fuel" allowing for the operation on natural gas or conventional fuel. These engines use spark plugs to ignite the fuel. "Dual-fuel" engines require diesel fuel in addition to natural gas for operation. Usually 5% to 35% diesel fuel is added to provide ignition for the CNG fuel [9]. The dual-fuel type of engine has been used for two Canadian car ferries and is proposed for the KINGS POINTER conversion. Engines may also be solely designed for CNG fuel. The JAMES C. ECHOLS was the first U.S. ferry to receive Coast Guard approval for the use of CNG as fuel in 1995 [3].

CNG Properties

The major differences between natural gas fuel systems and conventional fuel systems are the fuel properties shown in Table 1. The storage and use of this fuel in gas form poses some new hazards compared to liquid fuels. However, there are some physical characteristics that reduce hazards compared with conventional fuels such as diesel or gasoline.

There are characteristics of CNG that are advantageous as compared to gasoline or diesel fuel. CNG has a relatively high ignition temperature. The lower limit of the flammability range (volume required to form a flammable mixture) is greater than gasoline. Dispersion of CNG is greater than gasoline or diesel vapors due to the buoyancy of the fuel in air and high diffusion coefficient. Flame damage is generally due to thermal radiation, flame engulfment and smoke production [8]. CNG offers lower potential for thermal radiation damage due to a lower combustion temperature. The buoyant property of CNG in air and dispersion of the gas helps reduce damage due to flame engulfment. Smoke production is generally less with CNG as compared to diesel oil or gasoline.

There are potential economic and environmental benefits from the application of CNG fuel. This fuel generally costs less than diesel oil or gasoline. CNG fuel burns cleaner than conventional fuels with fewer nitrogen oxides, particulates and hydrocarbons [10]. CNG fuel may result in a 90% decrease in nitrogen oxide emissions as compared to diesel fuel [4]. The gas state of the fuel also eliminates the potential for water pollution which is present with liquid fuels such as gasoline or diesel [5]. There is an abundant domestic supply of natural gas. CNG has a high octane rating (122-130) which is a general indication of the ability of the fuel to burn more efficiently, improving engine performance [11]. CNG offers the opportunity for reduced engine maintenance due to less wear of the engine components affected by impurities in oil. Canadian passenger ferries (M.V. KLATAWA and KULLEET) operating on dual-fuel CNG systems have experienced a 300% increase in time between overhaul periods for the engines due to reduced engine wear [12].

There are also disadvantages to using natural gas fuel. The gas phase of this fuel and high storage pressure pose new hazards as compared to diesel or gasoline fuels. CNG is generally stored at pressures up to 4000 psig. This provides a potential source of explosion and rapid leak rates due to the high pressure. Impurities in CNG fuel have a large impact on increasing the corrosion potential for steel containers [13]. CNG requires about five times more storage tank volume than the equivalent amount of diesel fuel [1]. Natural gas is primarily composed of methane gas (CH_4) which is colorless, tasteless and odorless. In order to provide some odor for detection, mercaptan gas is often added. Title 49 CFR Section 192.635 requires odorant detection at 1/5 of the lower explosive limit.

Table 1 Fuel Properties [4] [14 *]

Characteristic	CNG	Gasoline	Diesel
Vapor Specific Gravity	.65	3.4	3.4
Diffusion coefficient (cm^2/second)	.16	.05	.03 *
Ignition temperature	1300 ºF	400 ºF	900ºF
Flammability Range	5.3% - 15%	< 2%	1% - 7.6%

CNG Standards

Currently, there is not a complete set of safety standards for CNG marine fuel applications. Title 46 Code of Federal Regulations (CFR) Part 154 contains guidance on safety standards for subchapter "O" vessels carrying bulk liquefied gases including LNG. These regulations allow for the use of cargo boil-off as fuel for main propulsion, boilers, and combustion engines. The standards provide some initial safety guidance for a CNG system's fuel lines, ventilation, valves, and gas detection. However, the safety items addressed in these regulations were not intended for other types of vessels and did not consider the high consequence safety concerns associated with passenger vessels.

Another source of CNG standards is 46 CFR 58.16, covering cooking and heating appliances. These requirements refer to the National Fire Protection Agency Standard 302 and the American Boat and Yacht Council, Inc. Standard A-22-78. These standards include requirements for the design, installation, and testing of cooking/heating systems. One requirement is the use of DOT or ASME (American Society of Mechanical Engineers) pressure vessels for CNG storage.

In general, pressure vessels for hazardous materials are required to comply with Title 46 CFR Part 54. This requires the pressure vessels be built to the ASME Pressure Vessel Code. However, the location and configuration of tanks for fuel storage are not addressed in the regulations.

CNG safety standards have been established for CNG fuel systems for vehicles.The National Fire Protection Association (NFPA) has published several standards for CNG fuel systems. For example, there are existing pressure vessel standards available for storage tank designs for automobile applications of CNG including: Department of Transportation, American National Standards Institute NGV-2, and American Society of Mechanical Engineers. The National Highway Transportation Safety Administration (NHTSA) adopted ANSI NGV-2 (voluntary automobile industry standard) for pressure vessels in 1994.

ANSI NGV2 allows for four different cylinder designs and technologies for vehicle storage cylinders as shown in Table 2. The variety of cylinder types was intended to create economic options for fuel storage since an estimated 70% of the additional cost of CNG fuel systems comes from the cost of fuel storage [15]. Table 3 identifies the reported failure rates of various pressure vessel construction types. This table shows that the predominant problem has been with leaking of composite pressure vessels.

Table 4 identifies several additional standards generated for CNG fuel application in the automotive

Table 2 Pressure Vessel Construction ANSI/IAS NGV2-1998

Container Type	Description
NGV2-1	All metal construction
NGV2-2	Metal-lined, hoop wrapped steel or aluminum.
NGV2-3	Metal-lined, fully wrapped aluminum composite.
NGV2-4	Nonmetallic-lined, fully wrapped all composite construction.

Table 3 Pressure Vessel Failures [14]

In-Service Cylinder Failures Worldwide				
Type	Numbers in service	In use since:	Rupture	Leaks
1	1,500,000	1974	10	0
2	80,000	1983	2	0
3	40,000	1992	3	0
4	15,000	1993	1	20

Table 4 CNG Automotive Fuel Standards

CNG Fuel Standard (Automotive)	Description
NFPA –52	Standard for Vehicular Fuel Systems (Including Fueling Facilities/ Ventilation req.)
FMVSS (DOT) 304	Compressed Natural Gas Container Integrity
ANSI NGV-1	Compressed Natural Gas Container Integrity
ANSI NGV-2	Basic Requirements for CNG Fuel Containers

industry. These standards may provide guidance for safe design. However, existing codes, standards and research efforts need to be carefully reviewed for suitability to marine applications of CNG fuel [5].

SYSTEM SAFETY USING RBT

While alternative fuels such as CNG reduce pollution hazards, other potential hazards are introduced. In order to understand the impact of hazards on system safety, information from a variety of sources is necessary. The evaluation of the safety of marine CNG fuel systems requires a good understanding of CNG properties and hazards under various operating conditions. Existing standards, specifications, regulations, and design guidelines should be examined for safety information with consideration for the applicability to a specific design. This information assists in conducting a system safety analysis.

A formal system safety technique offers a consistent approach to identify and resolve potential safety problems that may occur over the lifetime of the system. In order to consistently evaluate the safety of a proposed design, risk-based technologies may be used to help manage risk, offering a proactive way to identify and resolve safety issues. Risk assessment is the first step to evaluating the system safety. The gas state of the fuel and high compression along with the unique properties of the fuel and system design need to be considered when performing risk assessment. The control of risks is performed to reduce risk and design a system within acceptable safety limits. Combinations of inherent physical attributes of CNG, design technology, safety devices, and appropriate operational procedures can be used to produce safe CNG fuel designs.

<u>System Safety Techniques</u>

Risk-based technologies (RBT) are scientific methods or tools and processes used to manage the risks of a component or system. RBT methods can be classified into risk assessment, risk control, risk management, and risk communication as shown in Figure 1 [7]. Risk assessment consists of hazard identification, event-probability assessment, and consequence assessment. Risk control provides design and operation features to reduce risk. Risk management requires the definition of acceptable risk and comparative evaluation of options and/or alternatives through monitoring and decision analysis. Risk management provides decision techniques with consideration of risk assessment results and risk control measures. Risk communication involves communicating perceptions of risk, which vary depending on the particular audience.

The proposed process for the evaluation of CNG system safety is shown in Figure 2. The first step is defining the system through a system breakdown model. This model identifies the functional and physical relationship of system components. Hazard identification is used to identify hazards specific to a system design. A hazard is an act or phenomenon posing harm to some person(s) or thing(s) [16]. Risk assessment combines the probability and consequence of various possible scenarios to determine a risk value. Risk management determines the acceptability of a design, considering the results of the risk assessment in the decision process. The system design may need to be changed or the reliability of systems improved in order meet acceptable risk values. Design verification is used to verify the safe operation of a design through appropriate testing and monitoring.

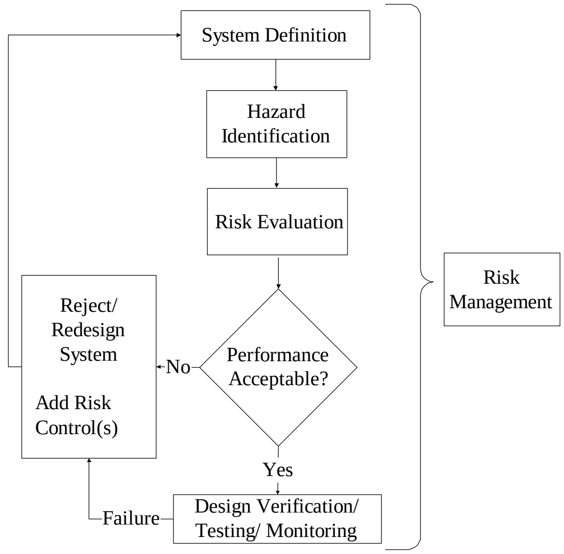

Fig. 2 Risk-based Approval Process for System Safety

System Definition

Defining the system is an important first step in performing a risk assessment. System definition requires the definition of physical and functional characteristics of a specific design. The examination of a system needs to be made in a well-organized and repeatable fashion for risk analysis to be consistently performed. A complete and systematic model definition helps ensure that important elements of a system are defined and extraneous information is omitted in order to address relevant safety issues.

The establishment of boundaries assists in developing the system definition. The decision on what the system boundary will be is partially based on what aspects of the system's performance are of concern [17]. For example, people are frequently overlooked as an important element of a system. The human element of a system should be included in the model for safety concerns. Environmental conditions may also be considered a component of a system including such variables as: weather, sea conditions, vessel traffic, and other hazards. Boundaries beyond the physical/functional system can also be established. Time may also be a boundary since an overall system model may change with time, over the life-cycle of the system. For example, material failure (corrosion or fatigue) may not be a problem early in the life of a system; however, this may be an important concern later in the life-cycle. Varied operational functions/activities may also be considered boundaries for the model.

The system breakdown model is a top-down division of a system into subsystems and components. This architecture provides boundaries for defining the system. Often the systems/ subsystems are initially identified by functional definitions that are decomposed to physical component levels of detail. The functional level of a system identifies the function(s) that must be performed for operation of the system. Further decomposition of the system into "discrete elements" leads to the physical level of a system definition identifying the hardware within the system. By organizing a system hierarchy (top down) rather than a fragmentation of specific systems, a rational, repeatable, and systematic approach to system modeling is achieved. Figure 3 identifies an example CNG system breakdown.

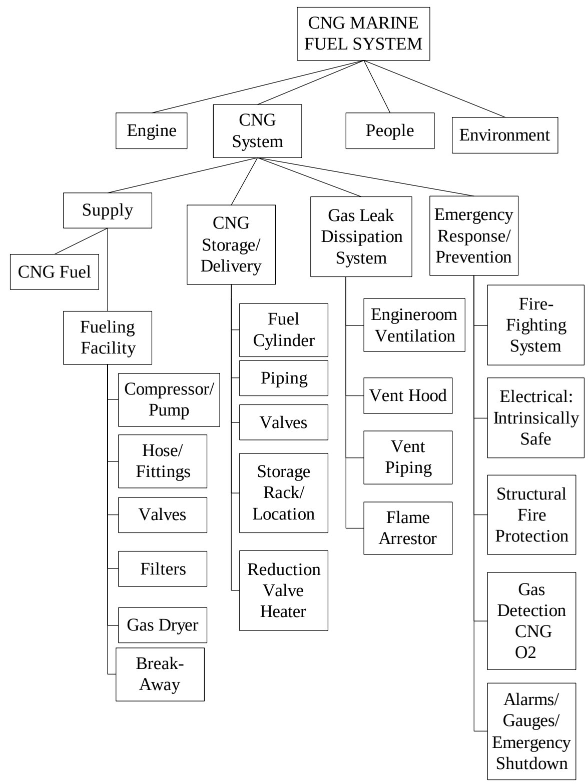

Fig. 3 CNG System Breakdown

While the system breakdown model provides boundaries for the systems, subsystem, and components, it does not provide a fully integrated view. Systems integration is an important part in evaluating the ability of a system to perform. The problem with segregating a system occurs when the subsystems are assembled to form the overall system, resulting in failures that are not obvious while viewing the subsystems separately [17]. Therefore, the interfaces should be evaluated. One method to represent the relationships of the systems functions is through a functional block diagram as illustrated in Figure 4 [18].

In addition to functional relationships of a system, human factors should be evaluated for the effect of people on the performance of a system. The potential for human error must be considered in performing a systems analysis. Also, the potential for corrective actions from fault situations should be considered [19]. The effect of the environment may also be included for its influence on the ability of a system to function.

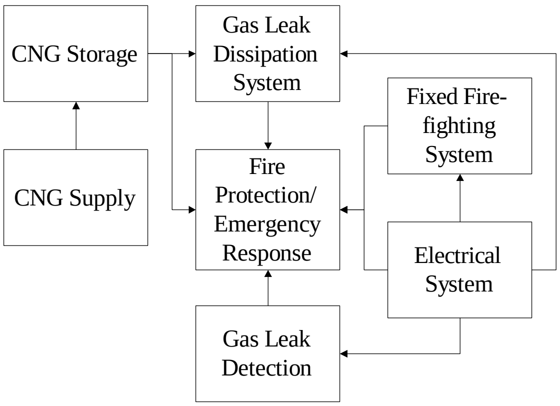

Fig. 4 CNG Functional Block Diagram

Hazard Identification

A hazard identifies a source of harm that interacts with people or things in a negative manner. Hazards may be identified through accident history, judgement of knowledgeable individuals, and/or risk assessment [1]. Some typical sources of marine risk/hazards are identified in Figure 5.

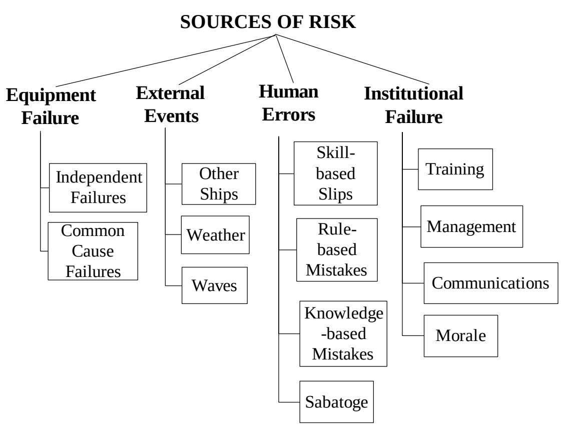

Fig. 5 Potential Sources for Marine Risk [21]

The determination of hazards for CNG begins with an understanding of the properties of the fuel. The following characteristics are important to identifying CNG hazards: storage parameters, tendency to form combustible mixture, ignition and explosion characteristics, means of controlling combustion, and environmental effects [8].

CNG fuel has two major hazards including the gas pressure and flammability. The high pressure of CNG fuel offers the potential for explosion and leaks. Gas leaks also may also present a hazard to health since CNG may displace oxygen, resulting in asphyxiation. The system design and operation should account for these hazards in developing a safe system.

CNG fuel stored in high pressures represents potential energy that can result in harmful scenarios if a high pressure leak occurs. A leak in the high pressure side of a CNG system can cause several problems. The momentum of the leaking gas may cause damage or injury depending on the rate of the leak. A catastrophic failure (explosion) of a pressure vessel or piping system may result in severe consequences.

A high pressure leak may also generate a fire hazard. The gas jet plume will have regions of gas in the explosive limit range that may create a “torch fire” if an ignition source is present. In addition, gas dissipating at high pressure may be extremely cold resulting in a loss of the buoyant properties in air. Adiabatic expansion of gas may cause the CNG temperature to be reduced to – 260 °F increasing the gas density to 1 $^{1}/_{2}$ times that of air [20]. Therefore, flammable gas mixtures may pool in low areas until the gas is heated and becomes buoyant. The addition of the momentum of the gas may also project the gas toward ignition sources that may not ordinarily seem hazardous.

A CNG leak is flammable if the concentration of gas is between the flammability limits. Within this region of gas concentration a spark, hot surface, or flame may ignite the gas mixture. However, a gas concentration outside the flammability range will not cause ignition. If the gas mixture is ignited, blast or fire damage may result. The potential hazards of ignition sources needs to be carefully evaluated and controlled.

CNG fuel leaks can only form a maximum volume of combustible mixture. The risk associated with a CNG fuel leak is dependant upon: the location, rate of CNG fuel leak and duration, tendency of fuel to form a combustible mixture, volume of the mixture, ventilation rate, and the time a mixture is in the viscinity of an ignition source [8]. These factors need to be considered when evaluating system risk.

The design and operating procedures can significantly minimize the risks associated with the hazard of a CNG fuel leak. A CNG fuel system should be designed to minimize the quantity and duration of fuel released from possible leaks. The addition of automatic isolation valves in the piping system may reduce the total amount of fuel released. Potential ignition sources should be avoided in the viscinity of areas where fuel leaks may occur. Adequate ventilation should be provided to control the potential for gas concentration above the lower explosive limit [1]. Gas detection systems can help identify fuel leaks and trigger alarms and/or automatic shutdowns. Additional means of controlling hazards are identified in the "Risk Control" section of this paper.

Risk

A fundamental goal of RBT is to provide a logical framework for risk evaluation and decision making. Risk measures may be used to model the safety performance of a system including uncertainties associated with an event. Risk can be defined as the potential of losses resulting from exposure to a hazard, and can be measured as a pair of the probability of occurrence of an event, and the outcomes or consequences associated with the event's occurrence [16]. This pairing can be represented by the following equation:

$$Risk \equiv \left[(p_1, c_1), (p_2, c_2), \ldots, (p_x, c_x)\right]$$

p_x is the occurrence probability of event x, and c_x is the occurrence consequences or outcomes of the event. Risk may also be represented as the product of likelihood of occurrence and the impact of an accident as follows:

$$RISK\left(\frac{Consequence}{Time}\right) = LIKELIHOOD\left(\frac{Event}{Time}\right) \times IMPACT\left(\frac{Consequence}{Event}\right)$$

Risk Assessment

Risk assessment is a technical and scientific process where risks of a system are modeled and quantified. Risk assessment can provide qualitative and/or quantitative information to decision makers for use in risk management. Qualitative risk analysis is usually used early in the design process or when data is not available for quantitative analysis.

Risk assessment or risk analysis provides the process for identifying hazards, event-probability assessment, and consequence assessment. The risk assessment process answers three basic questions: (1) What can go wrong? (2) What is the likelihood that it will go wrong? (3) What are the consequences if it does go wrong? The development of the scenarios for risk evaluation can be created deductively (e.g. fault tree) and/or inductively (e.g. failure mode and effect analysis (FMEA)). The likelihood or frequency can be expressed either deterministically or probabilistically. Varying consequence categories may be evaluated including such categories as: economic loss, loss of life, operability failure, injuries, an environmental impact.

The results of risk assessment are used for identifying system safety and comparing risks. Risks of individual failure scenarios can be prioritized using risk ranking or graphically displayed using a risk graph, as shown in Figure 17. Combining the individual event contributions to risk generates the calculation of the total expected risk value for a system.

Risk Assessment Methods

Risk assessment can be facilitated through several formal techniques. These different methods may contain similar approaches to answer the basic risk assessment questions; however, some techniques may be more appropriate than others for risk analysis depending on the situation.

Risk assessment techniques develop processes for identifying risk that can assist in decision making about the system. The logic of modeling the interaction of a system's components can be divided into two general categories: induction and deduction. Induction provides the reasoning of a general conclusion from individual cases [17]. Inductive analysis answers the question, "what are the system state(s) due to some event?" In reliability and risk studies this "event" is often some fault in the system. Several risk assessment approaches using the inductive approach include: Preliminary Hazard Analysis (PrHA), Failure Modes and Effects Analysis (FMEA), and event modeling using Event Tree Analysis (ETA). Deductive approaches provide reasoning for a specific conclusion from general conditions. This technique attempts to identify what modes of a system/ subsystem/component failure can be used to contribute to the failure of the system. Deductive logic answers the question, "how can a system state occur?" Deductive reasoning provides the logic for FTA (Fault Tree Analysis) or its complement Success Tree Analysis (STA).

Preliminary Hazard Analysis

Preliminary Hazard Analysis (PrHA) is a common RBT tool with many applications. This technique requires experts to qualitatively identify and rank the possible accident scenarios that may occur. It is frequently used as a preliminary way to identify and reduce the risks associated with major hazards of a system early in the design stage. PrHA is usually used in the early stages of design and operational planning to allow controls to be implemented in a cost effective manner. The PrHA process is shown in Figure 6.

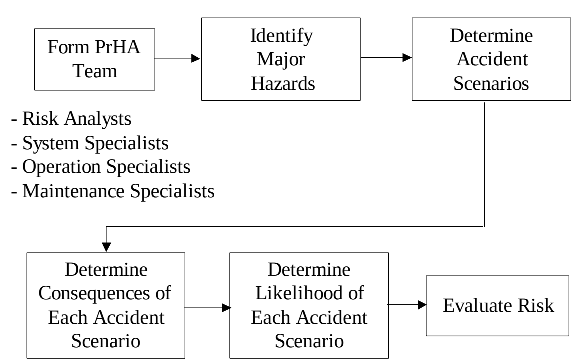

Fig. 6 Preliminary Hazard Analysis Process

Failure Mode and Effects Analysis

Failure Mode and Effects Analysis (FMEA) is another popular RBT tool considered to be more detailed than PrHA [22]. This technique has been introduced both in the national and international regulations for the marine industry. This analysis tool assumes a single point failure mode occurs in a system/component through some failure mechanism; the effect of this failure on other systems is then evaluated and a means of reducing the risk may be identified. A risk ranking can be developed for each failure mode for the effect on the overall performance of the system. FMEA can be used for quantitative evaluation of risk if failure probabilities are known.

Existing marine applications of FMEA for qualitative safety assessments include the International Maritime Organizations High Speed Craft Code, Title 46 Code of Federal Regulations Part 62, and Navigation and Inspection Circular 5-93 "Guidance for Certification of Passenger Carrying Submersibles." The FMEA process is identified in Figure 7.

Event Modeling

Event modeling is a systematic, and often most complete way to model accident scenarios and perform risk assessment. This RBT tool provides a framework for identifying scenarios to evaluate the performance of a system or component through system modeling. Event trees (ET) are used to inductively identify the scenarios of "high level" events. More detailed analysis of the events may be performed using the deductive logic of fault trees (FT). The combination of event trees (ET) and fault trees (FT) provides a structured model to evaluate risk. This logic identifies the different possible failure scenarios, assisting in qualitative risk assessment. The model can also be used for quantitative risk assessment if data is available.

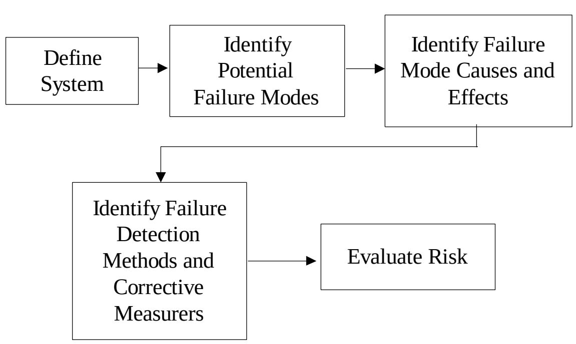

Fig. 7 Failure Mode and Effects Analysis Process

Event Tree Analysis

Event tree analysis is appropriate when the operation of some system/component depends on a successive group of events. Event trees identify the various combinations of event successes and failures as a result of an initiating event to determine possible failure propagation scenarios and control conditions. The event tree starts with an initiating event followed by some reactionary event. This reaction can either be a success or failure. If the event succeeds, the most commonly used indication is the upward movement of the path branch. A downward branch of the event tree marks the failure of an event. The remaining events are evaluated to determine the different possible scenarios. The scope of the events can include functions or physical systems that may provide some reaction to the initiating event. The final outcome of a sequence of events identifies the overall state (consequence) resulting from the scenario of events. Each event path represents a failure scenario with unique values of probability and consequence. The ability to address a complete set of scenarios is developed since all combinations of both the success and failure of the main events are included in the analysis. Different event trees can be created for different event initiators. Figure 8 is an example ET for the initial event of a gas leak occurring for a CNG system. It is important that all possible initiating events be included for a complete analysis. Other initiating events can be analyzed in a similar fashion for hazards such as fire or fuel system over-pressurization.

Based on the occurrence of an initiating event, event tree analysis examines possible system outcomes or consequences. This analysis tool is particularly effective to systematically show interdependence of system components, which is important in identifying events that at first might appear insignificant, but due to the interdependency may result in devastating consequences [23].

A quantitative evaluation of event tree probability values can be used for each event in an event tree to evaluate the probability of the overall system state for different consequences. Probability values for the success or failure of the events can be used to calculate the probability for a specific event tree sequence. Event probabilities in an event tree sequence can be provided as an input to the model or evaluated using fault trees/success trees. The probabilities of various sequences can be combined to determine the overall probability of a certain outcome (consequence). This addition of consequence evaluation of scenarios allows for generation of an overall risk value for the system.

CNG Event Tree

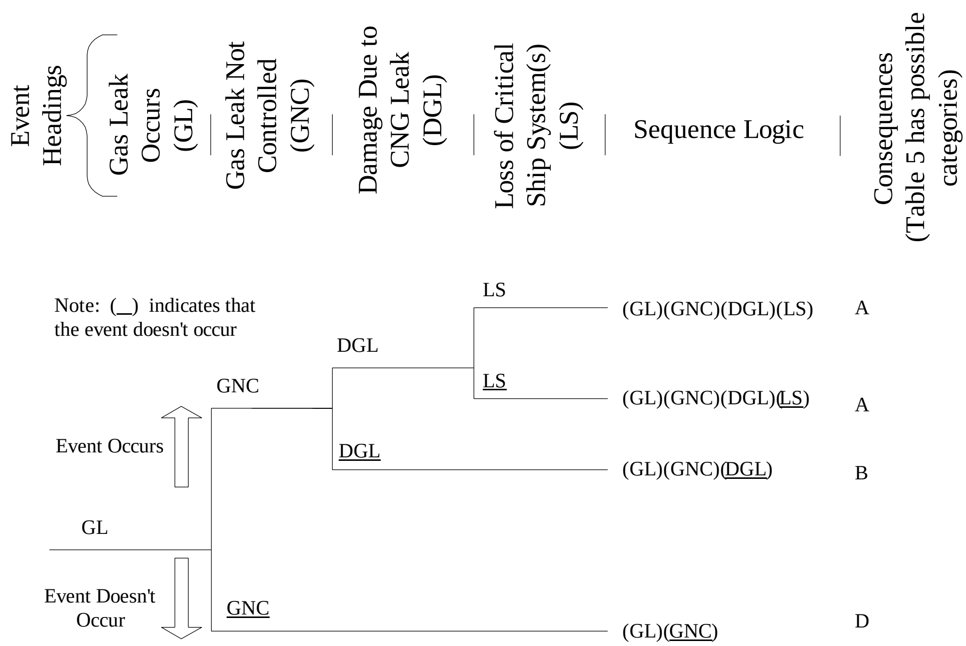

Fig. 8 CNG Event Tree

Fault and Success Tree Analysis

The probability of occurrence and scenario logic of the main events (event headings) of the ET can be determined using the logic of the fault tree (FT) or its complement the success tree. A FT is a graphical model created by deductive reasoning leading to various combinations of events that lead to the occurrence of some top event failure [23]. A success tree shows the combinations of events leading to the success of the top event. A success tree can be produced as the complement (opposite) of the fault tree by exchanging the boolean logic of "AND" and "OR" gates. Fault trees and success trees are used to further analyze the event tree headings (the main events in an event tree) to provide further detail to understand system complexities. In constructing the FT/ST only those failure/success events which are considered significant are modeled. This technique can be used for both qualitative and quantitative risk assessments [22]

Fault tree analysis starts by defining a top event, which is selected as an adverse event for FT analysis. An engineering system can have more than one top event. For example, a CNG fuel system may have the following top events for failure scenarios as shown in Figure 8: gas leak, gas leak not controlled, damage due o CNG leak, and loss of critical ship systems. Each top event needs to be examined using the following logic: in order for the top event to occur, what other events must occur? As a result, a set of lower-level events is defined. Also, the logic in which these lower level events are connected may be defined using boolean logic. The connectivity of these events is expressed using boolean logic with "AND" gates representing an intersection of events while the "OR" gate represents a union of events. The "AND" gate represents the simultaneous occurrence of conditions or events necessary to result in failure propagation up the tree. The "OR" gate indicates that each failure event is capable of leading to the next higher level of the tree [21]. The top event may be decomposed into intermediate events that correspond to further system detail. The bottom level of the model identifies the basic initiating events.

FTA requires the development of a tree-looking diagram for the system that shows failure paths and scenarios that can result in the occurrence of a top event. The construction of the tree should be based on the failure logic and the boolean logic gates. The symbols shown in Figure 9 are used for showing the logic between events [23].

The outcome of interest from the fault tree analysis is the failure logic and occurrence probability of the top event. Since the top event was

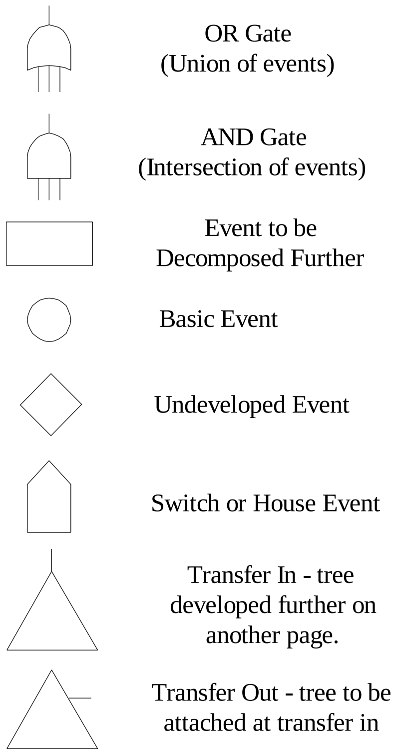

Fig. 9 Symbols for Fault Tree/ Success Tree Analysis

decomposed into basic events, its occurrence can be stated in the form of "AND" and "OR" combinations of the events. The resulting statement can be restated by replacing the "AND" with the intersection of the corresponding basic events, and the "OR" with the union of the corresponding basic events. Then, the occurrence probability of the top event can be computed by evaluating the probabilities of the unions and intersections of the basic events. The dependence between these events also affects the resulting probability of the system. Once this logic has been defined, possible failure scenarios of a system can be identified.

Figures 10 through 15 contain example fault trees for the events included in the event tree of Figure 8. Example calculations of logic combinations for quantitative analysis include the following examples. Figure 14 sub event “Fire Not Controlled Prior to Damage” uses “AND” gate logic to combine the events leading to the top event. Quantitatively the probability of the top event is calculated as (acronyms defined in Figure 14):

$$P(FNC) = P(SF \cap FEF) = P(SF) * P(FEF)$$

Figure 15 “Loss of Critical Ship System” uses “OR” gate logic to combine events as follows (acronyms are defined in Figure 15):

$$P(LC) = P(EF \cup PF \cup SF) = P(EF)+P(PF)+P(SF)-P(EF)*P(PF)-P(EF)*P(SF)-P(PF)*P(SF)$$

The subtraction of the product of the different pairs of events occurs because the events are not mutually exclusive. Careful consideration must be given to the dependence of events in order to account for conditional probability concepts [22].

For large fault trees, the computation of the occurrence probability of the top event can be difficult because of their size. Under these circumstances a more efficient approach is needed for assessing the reliability of a system such as the minimal cut sets approach. Each cut set is defined as a set of basic events where the joint occurrence of these basic events results in the occurrence of the top event [17]. A minimal cut set is a grouping of events with the condition that the non-occurrence of any one basic event from this set results in the non-occurrence of the top event. Therefore, a minimal cut set can be viewed as systems in parallel. In general, systems have more than one minimal cut sets. The occurrence of the top event of the system can, therefore, be the result of any one of these minimal cut sets. Therefore, the system can be viewed as the union of all the minimal cut sets. If probability values are assigned to the cut sets, a probability for the top event can be determined.

For complex systems, the number of failure paths can be quite large. The number of possible failure scenarios (assuming only two possible outcomes for each basic event) is given by:

$$\text{Failure Paths} = 2^n$$

Where n is the number of basic events in the system. Computer programs have been developed to assist in this analysis.

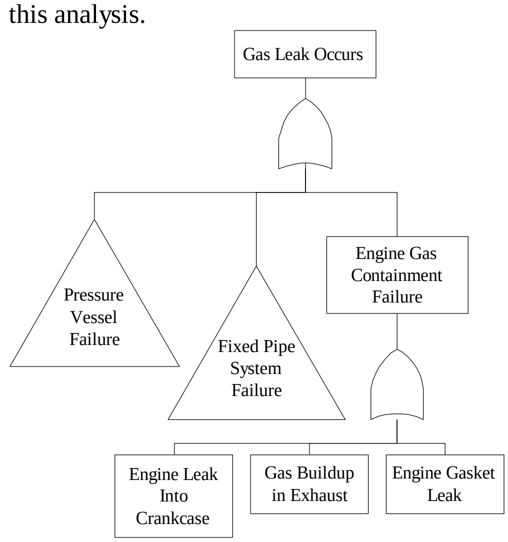

Fig. 10 Fault Tree: gas Leak Occurs

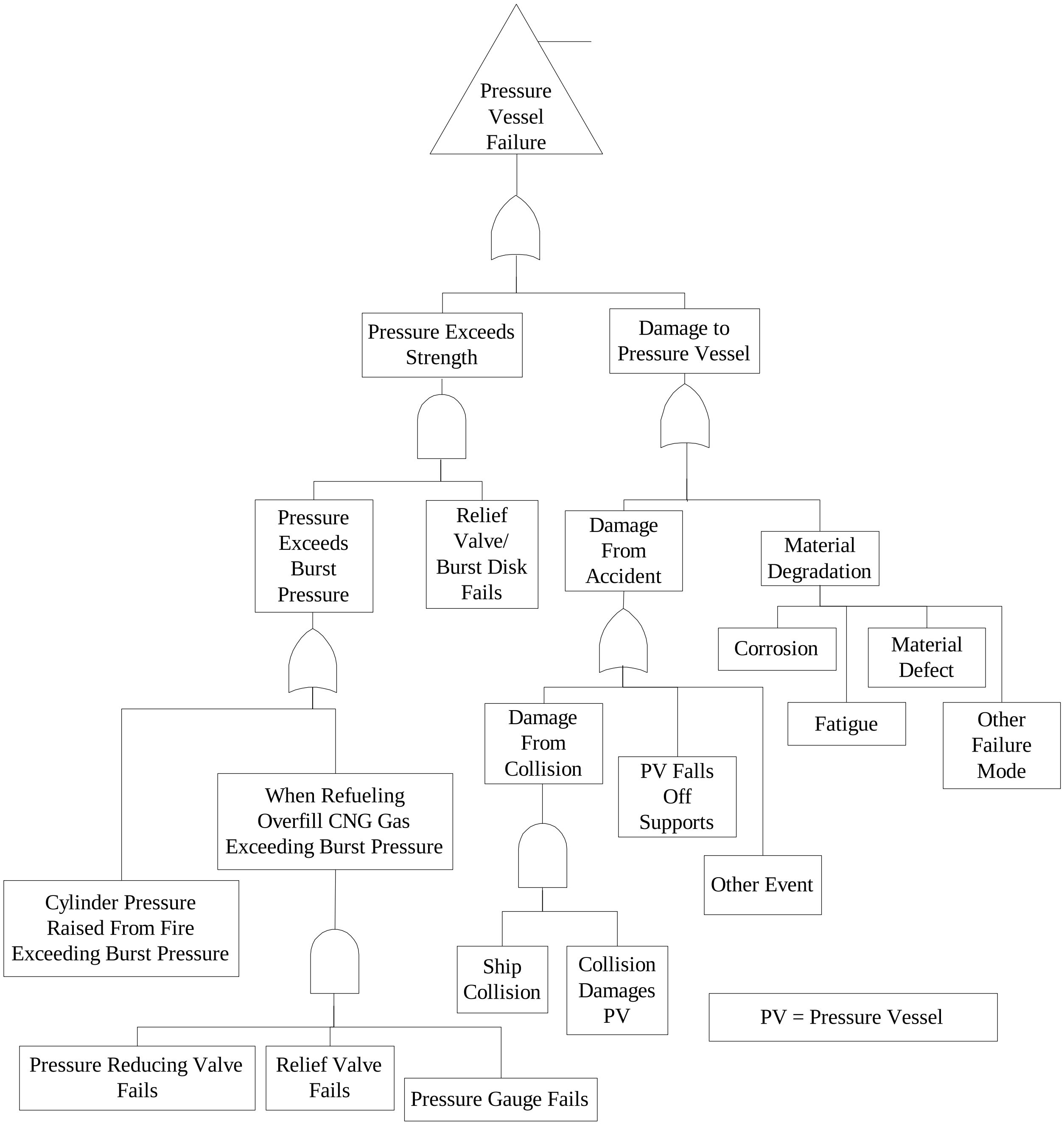

Fig. 11. Fault Tree: Pressure Vessel Failure

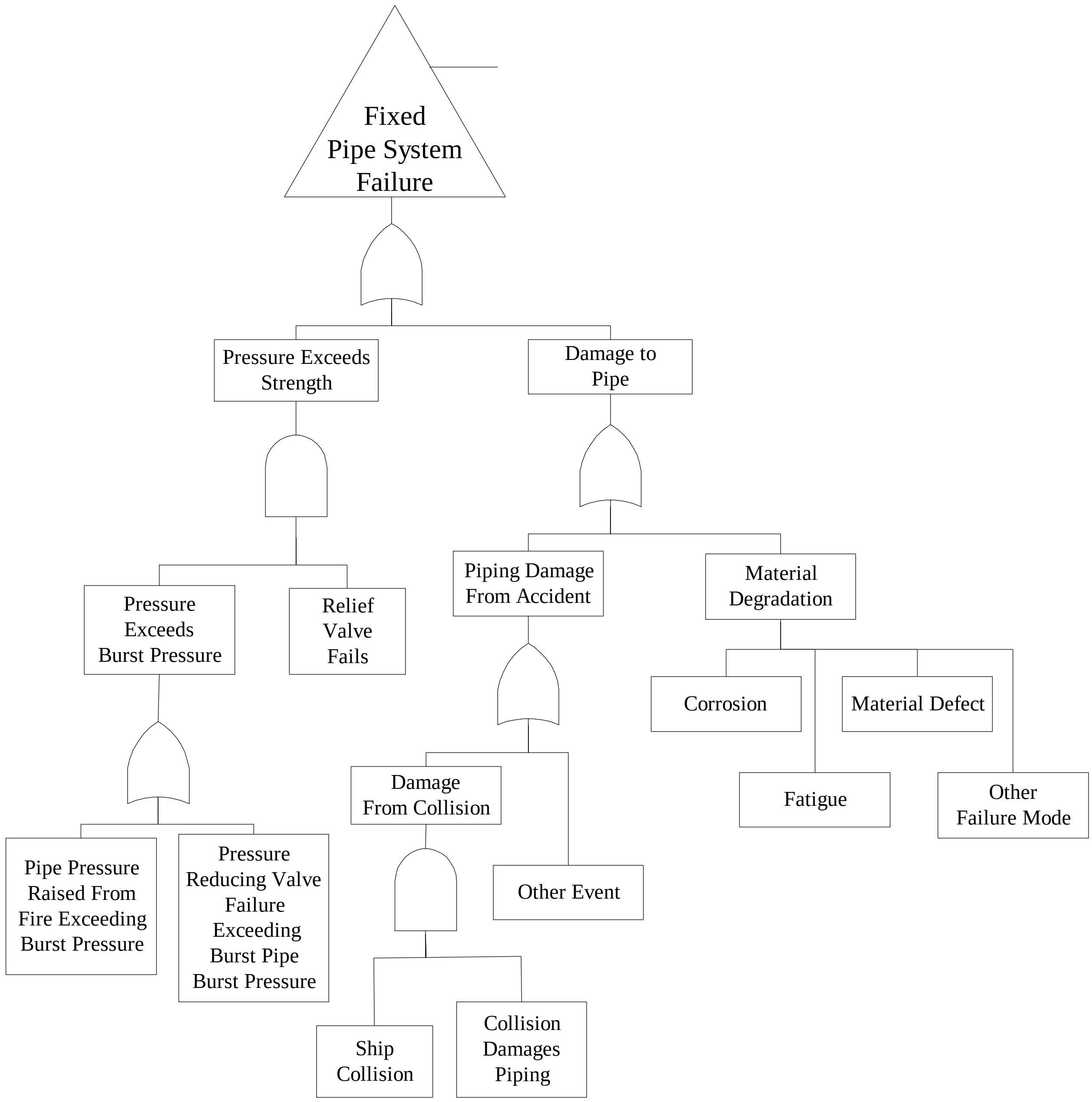

Fig. 12 Fault Tree: Fixed Pipe System Failure

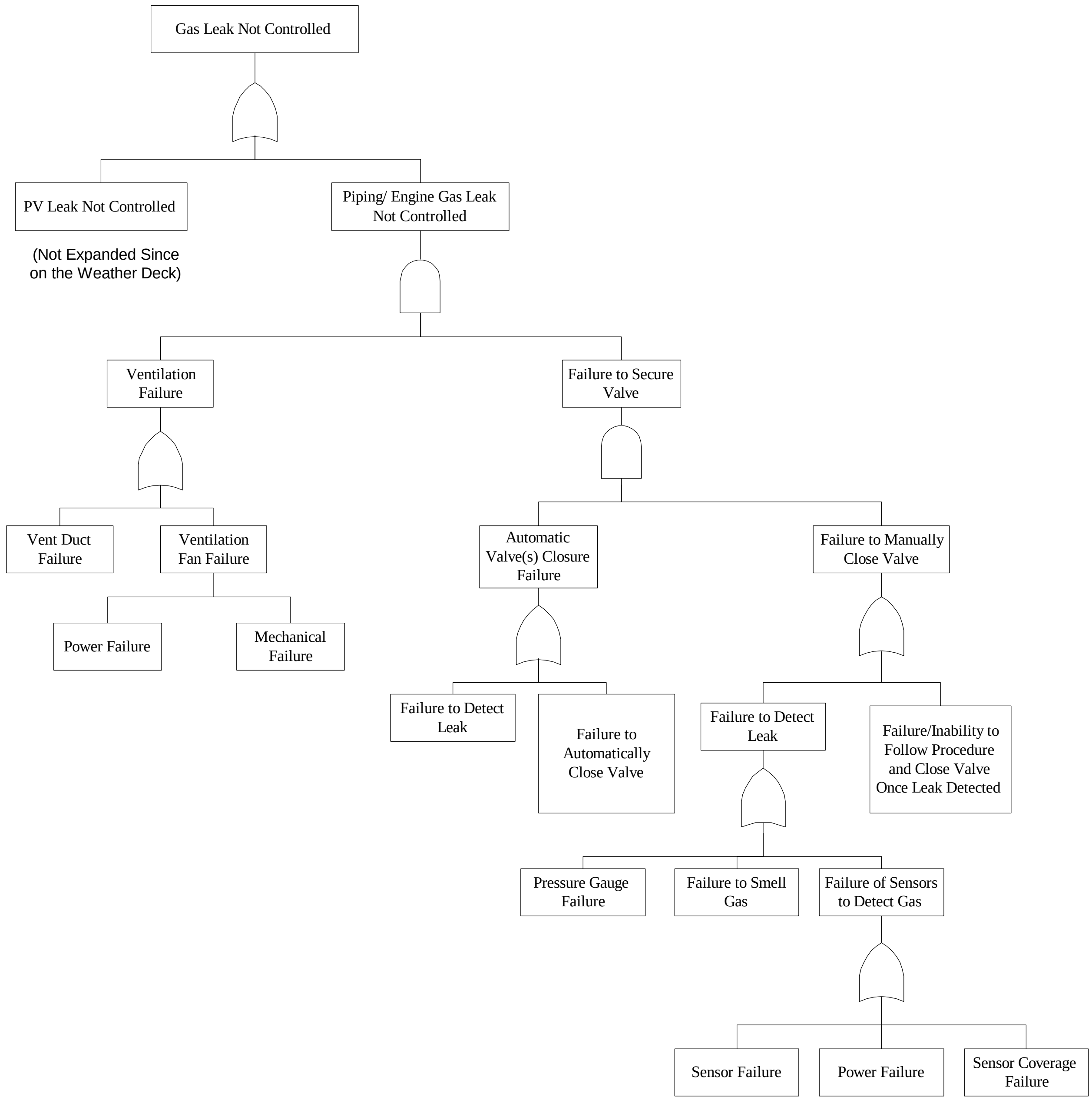

Fig. 13 Fault Tree: Gas Leak Not Controlled

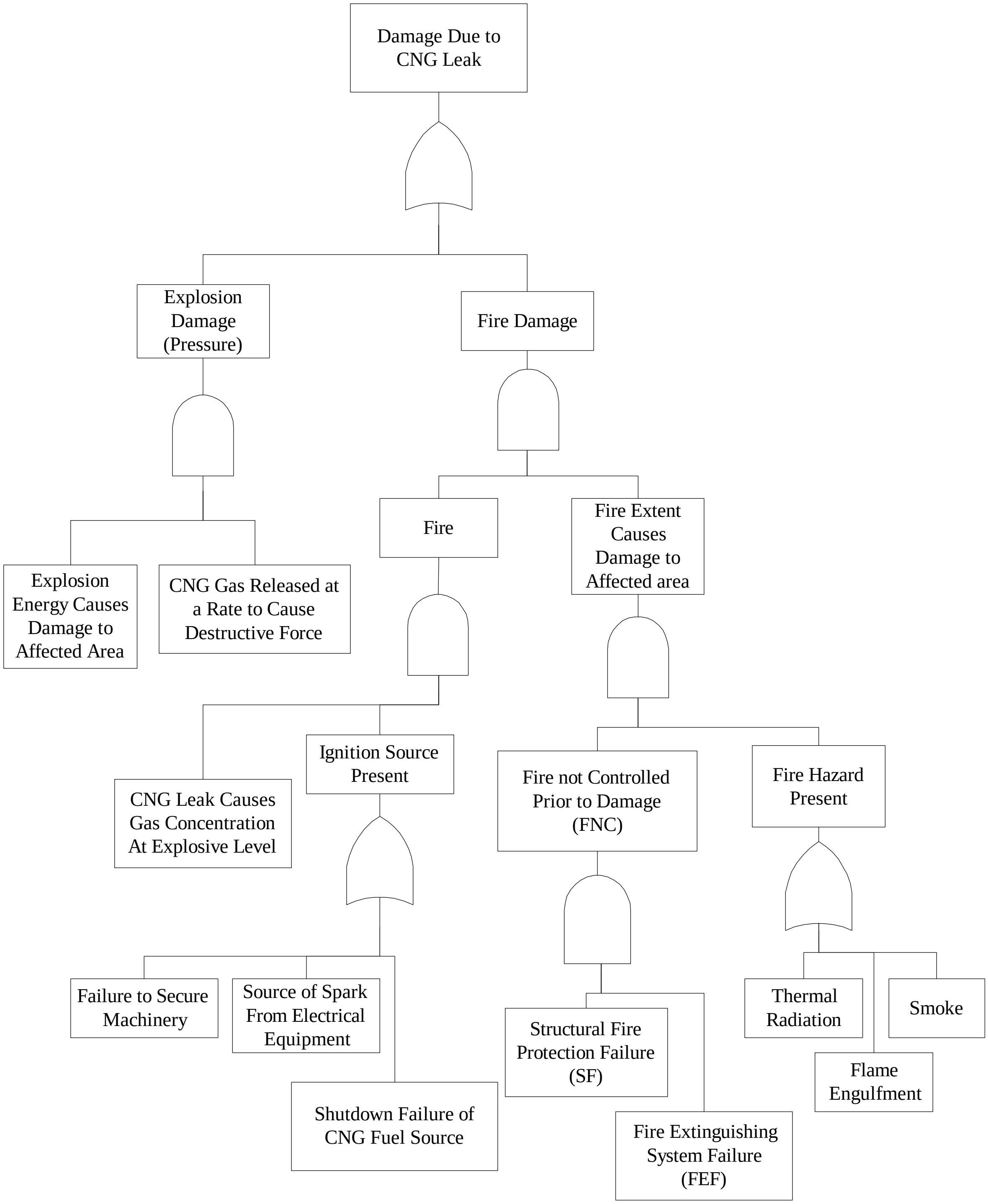

Fig. 14 Fault Tree: Damage Due to CNG Leak

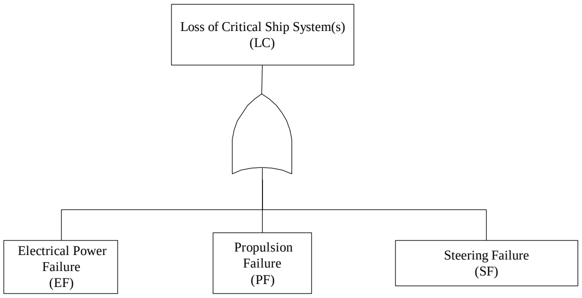

Fig. 15 Loss of Critical Ship System

Qualitative/Quantitative Risk Assessment

Risk assessment can also be categorized by how the risk is determined by using a quantitative or qualitative analysis. Qualitative risk analysis may use "expert" opinion to estimate probability and consequence often through linguistic expressions (high, medium, low, etc.). Example categories for qualitative consequence categories are shown in Table 5. Example qualitative probability categories are demonstrated in Table 6. These qualitative probability and consequence categories are only examples; they may be changed depending on the analysis. This subjective approach may be sufficient to assess the risk of a system, depending on the decisions to be made and available resources. Formal processes for expert-opinion elicitation have been developed to provide consistency in qualitative information gathering [16].

Quantitative analysis relies on statistical methods and databases that identify numerical probability and consequence values for risk assessment. The assignment of probability values to the various events in the risk model provides for a quantitative assessment of risk. This objective approach may examine the system in greater detail than qualitative estimates for measuring risk. However, the lack of data for risk assessment may present a problem if past experience and historical information are not available.

The selection of a quantitative or qualitative method depends upon the availability of data for evaluating the hazard and the level of analysis needed to make a confident decision. Qualitative methods offer analysis without detailed information, but the intuitive and subjective processes may result in different results by those who use them. Established procedures such as the Delphi technique provide consistent techniques for expert-opinion elicitation [16]. Quantitative analysis generally provides a more uniform understanding among different individuals, but requires quality data for accurate results. A combination of both qualitative and quantitative analysis can be used depending on the situation.

Another concern with the use of qualitative and quantitative data for risk assessment is uncertainty. Uncertainty in risk assessment can largely be attributed to uncertainties in parameter values and model design. Uncertainty may be affected by many factors: incomplete knowledge of potential failures, incorrect modeling assumptions, variability in accident circumstances, incomplete/conflicting data sources, and judgements by "experts" [22]. Quantitative analysis of uncertainty may use probabilistic measures of model input uncertainties and other mathematical techniques to identify and propagate uncertainties. Qualitative uncertainty estimates rely on subjective estimates of uncertainty. The identification of uncertainty estimates are important in making appropriate risk management decision considering the confidence in risk assessment results.

Table 5 Example Qualitative Consequence Categories

Category	Cost and Equipment Damage	Operability	Personnel Death/Injury	Environmental Impact
A	Loss of Ship > $10,000,000	Loss of Ship's Service Power	Fatalities	This will vary depending on the pollution source. For CNG the environmental threat is considered to be minimal since this is a gas lighter than air.
B	Major Damage > $100,000 - $10,000,000	Loss of Hotel, Cargo, and Industrial, and Auxiliaries	Lost Time Injuries	
C	Minor Damage > $1,000 - $100,000	Loss of Hotel, Cargo, and Industrial Systems	Minor Injuries	
D	< $1,000	Loss of Cargo and Industrial Systems	No Injury	

Table 6 Example Qualitative Probability Categories

Category	Description
I	*Likely*; may occur as often as once in an operating year
II	*May occur*, frequently between once a year and once in 10 operating years
III	*Not likely*, frequency between once in 10 years and once in 100 operating years
IV	*Very unlikely*, frequency between once in 100 years and once in 1,000 years

Human Reliability/ Risk Assessment

Risk assessment requires the performance analysis of an entire system composed of a diverse group of elements. The system definition readily includes the physical components of the system, however, humans are also part of most systems and provide significant contributions to risk. It has been estimated that nearly 90% of the accidents at sea are contributed to human error [24]. The human contribution to risk can be estimated from an understanding of behavioral sciences. Both the "hardware failure" and human error should be addressed in the risk assessment since they both contribute to system risk. Once the human error probabilities are determined, human error/failures are treated in the same fashion as hardware failures in performing risk assessment.

The evaluation of the human error contribution to risk may be determined by human reliability analysis (HRA) tools. HRA is the discipline that enables the analysis and impact of humans on the reliability and safety of systems. Human reliability analysis is generally considered to be composed of three basic steps: error identification, modeling, and quantification. Important results of HRA are determining the likelihood of human error as well as ways in which human errors can be reduced. When combined with system risk analysis, HRA models the effects of humans on the performance of the system.

Risk Control

Risk control measures may reduce risk by preventing an unfavorable scenario, reducing the frequency, and/or reducing the scenario consequence. Efforts for risk reduction are initially placed in the areas that contribute the greatest amount of risk. Techniques to improve (control) safety should be evaluated through engineering and administrative/operational controls. Engineering risk controls include such items as alternative system designs, improvements in system reliability, system redundancy, safety systems, and warning devices. Administrative/operational controls include operating procedures, training of personnel, and standard emergency procedures.

The safe design of a CNG system provides one way to control risk. For example, gas lines should be adequately protected from leaks. Two options that have been considered are the use of double-walled pipe or locating the piping in a ventilation duct. Ventilation systems may be used as a means to reduce gas concentrations. Gas detection monitoring in areas of potential leaks also contributes to the safety of a design. Additional risk reduction may result from automatic safety mechanisms if high gas concentrations are detected. Electrical equipment that may be in the presence of a combustible gas mixture should meet appropriate electric code requirements for being explosion proof or intrinsically safe [9]. Relief valves should be used to maintain the integrity of the fuel gas system in the event of a pressure increase beyond the design limits. Relief valve piping shall safely exit a space away from ignition sources. The location and size of fuel tank storage also influences the risk of the system. The use of oxygen detectors helps reduce health risk since CNG leaks may displace oxygen.

Improvements in CNG safety may also be generated from reducing human error. Error reduction is concerned with lowering the likelihood for error in order to reduce risk. The reduction of human errors may be achieved by human factors interventions or by engineering means [8]. Human factors interventions include improving training or improving the human-machine interface (alarms, procedures, etc.) based on an understanding of the causes of error. Training programs should be established for all those people included in the operation, fueling, and maintenance of the CNG fuel system. The necessary topics to be covered in the training depend on the responsibilities of the different personnel [1]. Personnel should understand the hazards of the CNG fuel system. A safety culture needs commitment from all participants in the design and operation of the fuel system. Risk communication is a key component to the success of developing a safety culture.

Maintenance activities should be performed taking into account the unique properties and hazards of the fuel. Procedures for de-fueling, gas freeing, or inerting should also be established [9].

A written emergency action plan provides a significant way to reduce risk through the identification of appropriate procedures to be taken in the event of an accident. This philosophy is currently used in developing requirements for Coast Guard oil spill response plans, operating manuals, and passenger security plans. This plan should be an integral part of the training program for operational effectiveness. Specific areas to include in the plan are: identification of emergencies, procedure for emergency actions, evacuation procedures, implementation of safety systems, and management actions [1].

Risk Management

Risk control and risk assessment contribute to risk management. Risk management is the process by which system design and operation decisions are chosen using data generated in the risk assessment and available risk control measures. Risk management requires the use of information from the previously described risk assessment to make educated decisions about system safety. Decisions to eliminate, mitigate, or accept hazards will result in appropriate actions for risk control.

Risk management requires the optimal allocation of available resources in support of goals. The goal of risk management is to reduce risk to an acceptable level and/or prioritize resources based on comparative analysis. Additional performance criteria need to be evaluated through comparative evaluation of options and/or alternatives for decision making. Risk managers make decisions based on risk assessment and other considerations including economical, political, environmental, legal, reliability, producibility, safety, and other factors. A complete analysis of decision analysis techniques is considered to be beyond the scope of this paper since this paper is focused on system safety evaluation. Further detail on decision analysis is provided in reference [16].

Risk Acceptance

Risk acceptance constitutes a definition of safety. The determination of acceptable levels of risk is important to determine the risk performance a system needs to achieve to be considered safe. If a system has a risk value above the risk acceptance level, actions should be taken to address safety concerns and improve the system through risk reduction measures. This concept is demonstrated in the risk graph shown in Figure 17. Example qualitative risk acceptance values can be identified on a risk matrix as shown in Table 7. These acceptance values may vary depending on risk management decisions.

The answer to the question "How safe is safe enough?" is difficult and may change due to different perceptions and understandings of risk. To determine "acceptable risk," managers may need to analyze alternatives for the best choice (Derby and Keeney 1993). In some industries, an acceptable risk has been defined by consensus. For example, the U.S. Nuclear Regulatory Commission has required reactors be designed such that the probability of a large radioactive release to the environment from a reactor incident shall be less than $1x10^{-6}$ per year [18]. Risk levels for certain carcinogens and pollutants have also been given acceptable concentration levels based on some assessment of acceptable risk. However, risk acceptance for many other government-regulated activities are not well stated. Another method for determining risk acceptance is the "as low as reasonably possible" (ALARP) methodology of reducing risk with reasonable consideration for technology and capital costs.

Qualitative criteria for risk acceptance are identified in several existing marine regulations. The International Maritime Organization High Speed Craft Code and the Coast Guard's Navigation and Vessel Inspection Circular (NVIC) 5-93 for passenger submersible design guidance both state that if the end effect is hazardous or catastrophic, a backup system and a corrective operating procedure is required. These references also state that a single failure must not result in a catastrophic event, unless the likelihood is extremely remote. Title 46 CFR Part 62 "Vital System Automation" also includes risk acceptance criteria for ship automated systems. Qualitative failure analysis is required for vital system automation systems including: propulsion controls, microprocessor-based system hardware, safety controls, automated electric power management, and any other automation that constitutes a safety hazard to the vessel or personnel. Acceptability of a design includes system monitoring, safety control requirements and "failsafe" designs. A "failsafe" state requires system design to the levels of least critical consequence.

Design guidelines established for CNG fueled buses, contain some additional guidance for risk acceptance [1]. These principles may provide some value for evaluating risk acceptance of marine system using CNG fuel:

- With normal operation there should be no unacceptable risks.
- Positive actions should be taken to enable system operation.
- Safety of a system in normal operation should not depend on actions of personnel.
- No single point failure in the system shall result in unacceptable or undesirable results.
- Unacceptable hazards should be eliminated through design.

Often the level of risk acceptance with various activities is implied. Society has reacted to risks through the developed balance between risk and potential benefits. Measuring this balance of accepted safety levels for various risks through data on accident histories provides a means for assessing society values. These threshold values of acceptable risk depend on a variety of issues including the activity type, industry, and users, and the societies values as a whole. Difficulty in determining risk acceptance is compounded by the fact that perception of risk often differs from objective measures. For example, perceived risk for unfamiliar activities may be at least ten times that of the actual risk measure [22]. Risk conversion factors can be used to help determine risk acceptance values based on the understanding of the public bias for unfamiliar, catastrophic, involuntary, and uncontrollable risks.

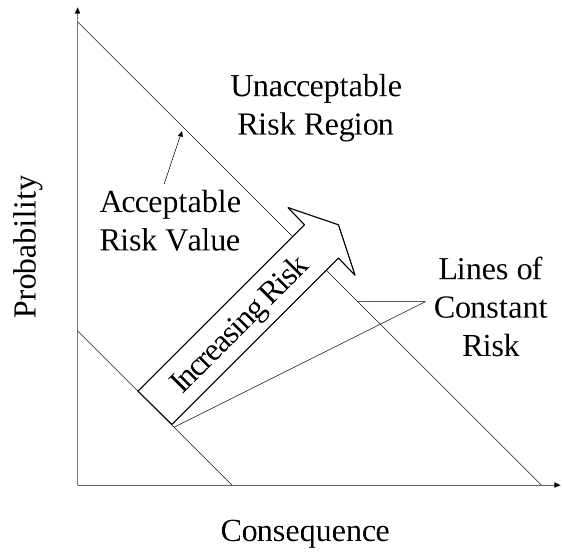

Fig. 17 Risk Graph

Table 7 Qualitative Risk Matrix

Severity of Consequence	Likelihood of Event			
	I (Likely)	II	III	IV (Very Unlikely)
A (High)	1	1	2	3
B	1	2	3	3
C	2	3	3	4
D (Low)	3	3	4	4

(1) *Unacceptable*. Should be mitigated to risk rank 3 or lower as soon as possible.
(2) *Undesirable*. Should be mitigated to risk rank 3 or lower within a reasonable time period.
(3) *Acceptable with controls.* Verify that procedures, controls, and safeguards are in place.
(4) *Acceptable as is.* No action is necessary.
Note: Likelihood and consequence categories are defined in Table 5 and Table 6.

Design Verification/ Testing/ Monitoring

The design and implementation of all safety critical items of a system should be subject to verification after construction of the system. The objective of the design verification is to verify that all the critical safety systems function as designed. Title 46 CFR Part 61 requires design verification testing for all automated vital systems. The tests verify the proper action of safety controls identified through risk analysis techniques and functional performance requirements. Specific testing is required to evaluate the operation and reliability of controls, alarms, safety features and interlocks. Test procedures are required to be submitted to the Coast Guard for approval. Additional testing requirements are included in relevant section of the CFR's. For example, requirements for testing piping systems are provided in 46 CFR Part 56.

This same testing methodology can be used for novel concepts such as CNG fuel applications to verify design safety features. A design verification process should include the following elements: identification of the factors on which safety depends, the identification of safety critical functions of the system, and verification that dependent factors are satisfied and safety critical functions are operating [1]. Monitoring provides information that may be used to identify the operational performance of a system.

Risk Communication

Risk communication can be defined as an interactive process of exchange of information and opinion among decision stakeholders such as individuals, groups, and institutions [24]. It often involves multiple messages about the nature of risk or expressing concerns, opinions, or reactions to risk managers. Risk communication may have a large impact on risk acceptance and the determination of acceptable safety criteria.

Risk communication provides the vital link between the risk assessors, risk managers, and the public to understand risk. However, this does not necessarily mean that risk communication will always lead to agreement among different parties. An accurate perception of risk is necessary to provide for rational decision making

The value of risk calculated from risk assessment is not the only consideration for risk managers. All risks are not created equal and society has established risk preferences based on the publics preferences [15]. Decision makers should take these preferences into consideration when making decisions concerning risk.

Risk communication can be enhanced and improved in three aspects: the process, the message, and the consumers [25]. The risk assessment and management process needs to have clear goals with openness, balance, and competence. The contents of the message should account for audience orientation and uncertainty, provide risk comparison, and be complete. There is a need for information guides that introduce risks associated with a specific technology, the process of risk assessment and management, acceptable risk, decision making, uncertainty, costs and benefits, and feedback mechanisms. Improving risk literacy is an essential component of the risk communication process.

The U.S. Army Corps of Engineers (USACE) has a 1992 engineering pamphlet (EP) on risk communication (EP 1110-2-8, 1992). The following items are suggested guidance in communicating risk:

- Risk communication must be free of jargon.
- Consensus of experts needs to be established.
- Materials cited, and their sources must be credible.
- Materials must be tailored to the needs of the audience.
- Risk data must be presented in a meaningful manner.

CONCLUSIONS

The introduction of alternative fuels for marine design presents a challenge for the commercial ship industry and the U.S. Coast Guard. The introduction of novel designs and technologies not covered by current standards need to meet adequate levels of safety. To facilitate the evaluation of a design for safety, formal risk technologies may be used. This paper identifies the important elements of analyzing the safety performance of a system using risk-based technologies. A suggested risk-based approval process for system safety evaluation is proposed as summarized in Figure 2. The techniques discussed in this paper can readily be applied to the evaluation of many different marine systems.

The objective of system safety evaluation is to develop a reliable and safe system. The prevention of accidents should be emphasized by systematically identifying hazards and mitigating the likelihood and consequences of accidents from the hazards to acceptable safety levels. RBT techniques offer a proactive means for safety management through the identification of hazards and reducing associated risks through risk control measures. These tools provide a formal and systematic way to address safety for novel designs when existing standards are not available to provide safety guidance. Design acceptance should be determined based on system design to adequate levels of safety, which may be qualitatively identified in a risk matrix and/or design guidelines.

Compressed Natural Gas may be a viable and safe alternative fuel for marine application provided that hazards are identified and controlled. Existing applications of CNG for fuel on marine vessels have proven the feasibility of CNG fuel for marine applications. The current evaluation of the KINGS POINTER using RBT will assist in addressing the safety issues of CNG fuel. This systematic approach helps address the safety issues without the existence of a complete set of regulations for a novel design. As design innovations and technologies advance marine system designs, continued applications of risk-based technologies will assist in the design and operation of safe marine systems.

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